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AIR FORCE REUSABLE ROCKET ENGINE PROGRAM

XLR129-P-1

FIRST ANNUAL REPORT

R. R. ATHERTON

PRATT & WHITNEY AIRCRAFT

DIVISION OF UNITED AIRCRAFT CORPORATION

FLORIDA RESEARCH AND DEVELOPMENT CENTER

TECHNICAL REPORT

AFRPL-TR-69-3—VOL I

JANUARY 1969

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LAMINATED CHAMBER COOLING MEANS AND A SLOT TUBE INJECTOR CONCEPT

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AIR FORCE REUSABLE ROCKET ENGINE PROGRAM

XLR129-P-1

FIRST ANNUAL REPORT

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FOREWORD

This annual report describes the Air Force Reusable Rocket Engine Program XLR129-P-1 conducted during the period 6 November 1967 to 6 November 1968, and is submitted in accordance with the requirement of Contract F04611-68-C-0002.

This effort is the second phase of the Air Force Cryogenic Rocket Engine Advanced Development Program, Project 2 of the Program Element 63048F.

This publication was prepared by the Pratt & Whitney Aircraft Florida Research and Development Center as report PWA FR-2972.

This report contains no classified information extracted from other classified documents.

Rocket Propulsion Laboratory personnel who have monitored specific areas of this program and who have made contributions to the program are as follows: Captain Robert E. Probst - Turbomachinery and Controls, Captain James Kephart and Captain Vernon Mahugh - Combustion Devices.

This Technical Report has been reviewed and is approved.

Ernie D. Braunschweig
Captain, USAF
Program Manager
Air Force Rocket Propulsion Laboratory

UNCLASSIFIED ABSTRACT

The objective of this program is to demonstrate the performance and mechanical integrity of a 250,000-lb thrust reusable oxygen/hydrogen rocket engine designated the XLR129-P-1. The program, which is sponsored by the Air Force Rocket Propulsion Laboratory, is being accomplished at Pratt & Whitney Aircraft and consists of design, analysis, fabrication, and test of all the engine components and the complete demonstrator engine. This effort is the second phase of the Air Force Cryogenic Rocket Engine Advanced Development Program, Project 2 of Program Element 63048F. During the first year, experimental evaluation was conducted in the areas of a fixed fuel area preburner injector, hydrogen cooled roller bearings, compact pump inlets, lightweight nozzle fabrication techniques, and selected control valves. Under the fixed fuel area preburner injector evaluation, a new full-scale preburner injector was designed, fabricated, and tested that produced a uniform temperature profile suitable for use in the engine. Under the roller bearing durability tests, four bearing configurations surpassed the test duration goal at the design operating conditions. Under the pump inlet evaluation, an elbow type of inlet with turning vanes was selected for both the fuel and oxidizer turbopumps. Under the nozzle fabrication investigation, it was concluded that the internal corrugated type of construction was best for the two-position nozzle. Under the controls component tests, both a hoop shutoff seal and a cam-actuated shutoff seal have proven to be potentially feasible types of seals for use in the main chamber oxidizer valve, which is a butterfly valve. Also, pressure balance configurations of piston rings used in the preburner oxidizer valve have demonstrated acceptable wear leakage and actuator force characteristics. Under the Component Development Task, designs have been initiated for the preburner injector, main burner injector, main burner chamber, nozzles, transition case, fuel turbopump, oxidizer turbopump, fuel low-speed inducer, oxidizer low-speed inducer, and the control components. The demonstrator engine design has also been started.

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TABLES

TABLES (Continued)

LIST OF ABBREVIATIONS AND SYMBOLS

Item	Definition
A	Effective area
A_{cd}	Effective flow area
A_o	Overall area
A_s	Secondary area
A_S	Slot area
A_T	Tube area
BDC	Bottom dead center
c^*	Characteristic velocity
d	Distance
Et	Modulus x thickness^3
F_A	Axial force
F_C	Clamping force
F_R	Radial force
FS	Flow split
g	Gravitational constant
G_R	Radial pressure unbalance
h	Turbine inlet enthalpy or height
H_A	Drag
H_R	Radial friction
I	Inertia
K_c	Stress
L/D	Length-to-diameter ratio
M_G	Pressure moment due to pressure unbalance
M_H	Pressure moment due to friction
P	Static pressure
P_c	Chamber pressure
Pr	Pressure x radius
P_H	High pressure
P_L	Low pressure
Q/A	Heat flux
Q/N	Unit flow
RA	Area reduction
R_T	Nozzle weight parameter

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

Item	Definition
S	Suction specific speed
t	Thickness
T	Total temperature
T_{fuel}	Total fuel temperature
TDC	Top dead center
UP	Unit pressure
$\dot{w}_p$	Primary flow
$\dot{w}_t$	Total engine flow
W/D	Slot width-to-orifice ratio
ΔL	Length extension
ΔP	Pressure differential
ΔT	Temperature differential
ϵ	Nozzle area ratio
η_c*	Characteristic exhaust velocity efficiency

SECTION I
INTRODUCTION

(U) The Air Force XLR129-P-1 Reusable Rocket Engine Program is an Advanced Development Program that covers a 54-month period starting 6 November 1967 and ending 6 May 1972. The overall objective of this program is to demonstrate the performance and mechanical integrity of a 250 K oxygen/hydrogen reusable rocket engine having the characteristics outlined in Table I.

(C)(U) Table I. Demonstrator Engine Characteristics

Nominal Thrust	250,000-lb vacuum thrust with area ratio of 166:1 244,000-lb vacuum thrust with area ratio of 75:1 209,000-lb sea level thrust with area ratio of 35:1
Minimum Delivered Specific Impulse Efficiency	96% of theoretical shifting I_s at nominal thrust: 94% of theoretical shifting I_s during throttling
Throttling Range	Continuous from 100 to 20% of nominal thrust over the mixture ratio range
Overall Mixture Ratio Range	Engine operation from 5.0:1 to 7.0:1
Rated Chamber Pressure	2740 psia
Engine Weight (with 75:1 nozzle)	3520 lb (with flight-type actuators and engine command unit) 3380 lb (less flight-type actuators and engine command unit)
Expansion Ratio	Two-position booster-type nozzle with area ratios of 35:1 and 75:1
Durability	10 hours time between overhauls, 100 reuses, 300 starts, 300 thermal cycles, 10,000 valve cycles
Single Continuous Run Duration	Capability from 10 seconds to 600 seconds
Engine Starts	Multiple restart at sea level or altitude
Thrust Vector Control	Amplitude: $\pm$ 7 deg; Rate: 30 deg/sec; Acceleration: 30 rad/sec^2

(C)(U) Table I. Demonstrator Engine Characteristics (Continued)

Control Capability	± 3% accuracy in thrust and mixture ratio at nominal thrust. Excursions from extreme to extreme in thrust and mixture ratio within 5 seconds.
Propellant Conditions	LO_2: 16 ft NPSH from 1 atmosphere boiling temperature to 180°R LH_2: 60 ft NPSH from 1 atmosphere boiling temperature to 45°R
Environmental Conditions	Sea level to vacuum conditions Combined acceleration: 10 g's axial with 2 g's transverse, 6.5 g's axial with 3 g's transverse, 3 g's axial with 6 g's transverse
Engine/Vehicle	The engine will receive no external power, with the exception of normal electrical power and 3000-psia helium from the vehicle

(U) The entire program consists of five major tasks and specific subtasks as follows:

Task 1.1 - Supporting Data and Analysis

- Subtask 1.1.1 - Fixed Fuel Area Preburner Injector Evaluation
- Subtask 1.1.2 - Roller Bearing Durability Tests
- Subtask 1.1.3 - Pump Inlet Evaluation
- Subtask 1.1.4 - Nozzle Fabrication Investigation
- Subtask 1.1.5 - Controls Component Tests

Task 1.2 - Component Development

- Subtask 1.2.1 - Preburner Injector
- Subtask 1.2.2 - Main Burner Injector
- Subtask 1.2.3 - Nozzles
- Subtask 1.2.4 - Main Burner Chamber
- Subtask 1.2.5 - Transition Case
- Subtask 1.2.6 - Fuel Turbopump
- Subtask 1.2.7 - Oxidizer Turbopump
- Subtask 1.2.8 - Fuel Low-Speed Inducer
- Subtask 1.2.9 - Oxidizer Low-Speed Inducer
- Subtask 1.2.10 - Control System

Task 1.3 - Engine Integration and Demonstration

Task 2.0 - Flight Engine

Task 3.0 - Engineering Support

A. FIXED FUEL AREA PREBURNER INJECTOR EVALUATION

(C) The Fixed Fuel Area Preburner Injector Evaluation subtask objective was to design, fabricate, and test a fixed fuel area preburner injector that will provide a temperature profile of less than 150°R peak-to-average at an average temperature of 2325°R operating satisfactorily on engine cycle injection pressure differences and propellant temperatures.

B. ROLLER BEARING DURABILITY TESTS

(C) The Roller Bearing Durability Tests subtask objective was to evaluate 55 x 96.5 mm roller bearings for use in the 250K fuel turbopump. Testing was conducted with liquid hydrogen cooling at a shaft speed of 48,000 rpm and with a 1700-lb radial load. Preliminary bearing tests, during Phase I, (Contract AF04(611)-11401) had indicated that it was feasible to operate a roller bearing at these conditions, but that roller end wear and skewing could affect bearing durability. The current phase of this program investigates the effect of roller length-to-diameter ratio, roller crowning, internal fits, and roller-to-side rail clearance on roller end wear and bearing durability.

C. PUMP INLET EVALUATION

(U) The Pump Inlet Evaluation subtask objective was to obtain supporting data for the design of the inlet configuration to be used on the liquid hydrogen and liquid oxygen turbopumps. Because of engine packaging considerations, the proposed demonstrator engine has a flow distributor at the inlet to each main turbopump. The effect of an inlet flow distributor on the head-flow and suction characteristics of the inducer was investigated using water as the test fluid. These data were used to design a suitable pump inlet configuration within the demonstrator engine envelope.

D. NOZZLE FABRICATION INVESTIGATION

(U) The Nozzle Fabrication Investigation subtask objective was to provide additional data and information to support the subsequent design of the two-position nozzle. Sample nozzle panels were fabricated to evaluate manufacturing techniques and subjected to hydraulic stress and thermal cycling tests to determine the structural characteristics.

E. CONTROLS COMPONENT TESTS

(C) The Controls Component Tests subtask had several objectives. Tests were to be conducted on the main chamber oxidizer valve to evaluate four shutoff seals and shaft lipseals to meet the leakage goals established for the valve. Tests were also to be conducted on the preburner oxidizer valve to investigate various surface coatings for improved endurance and a pressure balanced piston ring design. Analytical and experimental investigations were to be conducted to formulate and improve a computer program model to provide a good stress and deflection analysis capability for the seal rigs to be designed under the component development phase of this program.

F. PREBURNER INJECTOR

(C) The Preburner Injector subtask overall objectives are to design, build, and test a preburner injector that will provide a 150°R temperature profile at maximum operating conditions, acceptable start transients, and stable efficient combustion.

G. MAIN BURNER INJECTOR

(U) The Main Burner Injector subtask overall objectives are to design, build, and test a lightweight main burner injector that introduces, atomizes, and mixes liquid oxidizer with the hot fuel-rich turbine discharge (preburner combustion products) in such a manner that efficient and stable combustion results over the full operating range of thrust and mixture ratio.

H. NOZZLES

(U) The Nozzles subtask objectives are to provide a fixed regeneratively cooled nozzle and an extendable two-position nozzle skirt and translating mechanism for the demonstrator engine.

I. MAIN BURNER CHAMBER

(U) The Main Burner Chamber subtask overall objectives are to design, build, and demonstrate, through full-scale testing, performance and operational capability of a lightweight, durable thrust chamber for use in the demonstrator engine program over the specified throttling and mixture ratio ranges.

J. TRANSITION CASE

(C) The Transition Case subtask objective is to demonstrate the structural adequacy of the engine transition case when operating at an internal pressure of 4856 psia with internal combustion gas temperatures as high as 2325°R. This subtask will also verify the structural and cooling capability of the transition case cooling liner. Hot testing prior to full-scale demonstrator engine use will be done in three steps. The first step will be tests with the preburner to establish the temperature profile at the turbine inlet. The fuel turbopump will be mounted in the case for the second series of tests. These tests will demonstrate turbine performance at engine peak conditions. The third test series will be conducted in the staged combustion configuration to verify main burner injector, main burner chamber, and nozzle performance, and operation.

K. FUEL TURBOPUMP

(C) The Fuel Turbopump subtask objective is to demonstrate performance and operational capability for use in the demonstrator engine program. Preliminary analyses indicate that the turbopump must be capable of operating at a maximum speed of 48,000 rpm, a pressure rise of 5654 psid, and flow rate of 99.3 lb/sec at a mixture ratio of 5.0. In addition, the turbopump must demonstrate satisfactory starting and stable operation

over the engine operating range of 20 to 100% thrust and mixture ratio of 5.0 to 7.0. Life will be based on a 10-hour time between overhaul and 100 reuses (300 starts and 600 seconds maximum run duration). Bearing and seal life will be demonstrated by conducting 10-hour tests on ten sets of bearings and seals.

L. OXIDIZER TURBOPUMP

(C) The Oxidizer Turbopump subtask objective is to demonstrate performance and operational capability for use in the demonstrator engine program. Preliminary analyses indicate that the turbopump must be capable of operating at a maximum speed of 25,925 rpm, a maximum pressure rise of 6785 psi without recirculation, a maximum flow of 548 lb/sec. In addition, the turbopump must demonstrate satisfactory starting and stable operation over the engine operating range of 20 to 100% thrust and mixture ratio of 5.0 to 7.0. Life will be based on a 10-hour time between overhaul and 100 reuses (300 starts and 600 seconds maximum run duration). Bearing and seal life will be demonstrated by conducting ten 10-hour tests on ten sets of bearings and seals.

M. FUEL LOW-SPEED INDUCER

(C) The Fuel Low-Speed Inducer subtask objective is to demonstrate performance and operational capability for use in the demonstrator engine program. Life will be based on a 10-hour time between overhaul and 100 reuses (300 starts).

N. OXIDIZER LOW-SPEED INDUCER

(C) The Oxidizer Low-Speed Inducer subtask objective is to demonstrate performance and operational capability for use in the demonstrator engine program. Life will be based on a 10-hour time between overhaul and 100 reuses (300 starts)

O. CONTROL SYSTEM

(U) The Control System subtask overall objectives are to provide a dependable control system for demonstrator engine testing to meet the performance and operational objectives, and to provide assurance that flight control designs can be developed and ultimately implemented to meet the standards for a man-rated flight system.

P. ENGINE INTEGRATION AND DEMONSTRATION

(U) The Engine Integration and Demonstration task objectives are to conduct the hydrodynamic, thermodynamic, and mechanical analyses and design of the demonstrator engine assembly by integrating the component designs of Task 1.2; to fabricate engine assembly hardware and an engineering mockup; to assemble two complete demonstrator engines; and to test these engines to demonstrate the engine thrust, specific impulse, throttling range, mixture ratio range, chamber pressure, weight, expansion ratio, starting, control capability, and propellant conditions.

Q. FLIGHT ENGINE

(U) The Flight Engine task objective is to define the flight engine configuration that could result from an engineering development program based on the proposed engine concept. Detailed analytical and preliminary design studies will be conducted concurrently with the demonstration engine test program to define the configuration and capabilities of the flight engine.

R. ENGINEERING SUPPORT

(U) The Engineering Support task objective is to provide the engineering personnel required to accomplish the necessary management control of the design, fabrication, test, and data to support the engine demonstration program. This task includes the preparation of the Monthly Status Reports, the Component Design Handbook, the Program Plan, the Annual, Milestone, and Final Reports, the Program Reviews, and other special technical reports.

SECTION II
SUMMARY

(C) Under the Fixed Fuel Area Preburner Injector Evaluation subtask, an injector was fabricated using an existing Phase I preburner injector body modified to allow incorporating 252 dual-orifice, tangential-swirl oxidizer, fixed concentric fuel area elements. This injector was tested to evaluate operation and temperature profile over the range of conditions equivalent to engine mixture ratios from 5.0 to 7.0, starting and thrust levels of 20% to 100%. The fixed area preburner injector must operate on cold gaseous hydrogen and liquid oxygen. The gaseous fuel allows throttling the fuel while still maintaining a suitable injection velocity because of the compressible fuel density change. On the liquid oxygen side, a dual-orifice principle was applied to a slot swirler element for providing suitable injection velocity over the throttle range for the essentially incompressible liquid oxygen. The slot swirler element was selected because of its very fine atomization and mechanical simplicity. Initial water flow tests of the liquid oxygen injection element were conducted to determine the element discharge coefficients, cone angle, and a measure of its stability using pulse testing. The originally selected element (0.095-inch inside diameter) had undesirable vortex instability characteristics at several flow levels. A model test program was then conducted to develop a stable oxidizer injection element, which has a 0.124-inch inside diameter. Fourteen full-scale preburner combustion tests were conducted with the fixed fuel area preburner. The preburner temperature profile was significantly improved over the results obtained with the variable area preburner injector tested under Contract AF04(611)-11401. A peak-to-average combustion temperature profile of 76°R in a radial plane was demonstrated at an average temperature of 2388°R. Damaged oxidizer elements in a section of the injector in line with the temperature rake in a second plane distorted the temperature profile causing a reduction in average temperature to 2325°R and a subsequent increase in measured peak-to-average temperature of 215°R. Four ignition tests were conducted to determine if the preburner would ignite with a secondary helium purge flow rate and the low engine starting tank head flow rate; successful ignition and sustained combustion occurred during all four tests. Four additional tests were programmed to simulate the engine start transients from the ignition flow rates to the 20% flow rate level. Purge timing during shutdowns was adjusted to study the best engine shutdown sequence. During testing of the preburner injector, low frequency combustion instability was encountered at thrust levels below 25% and several tests were programmed to obtain data on influential parameters. An analog model of the preburner injector, combustion chamber, and a portion of the test stand was constructed to determine the influence of various parameters on stability. Water flow tests of the injector assembly and single element test rigs were also made. It was concluded from the test data, where high pressure drop orifices had been installed in the facility lines, that the test facility line volumes were not the cause of the chugging. The analog model that duplicated the test results of frequency and amplitude fairly well indicated that the low secondary pressure drop and large secondary volume contributed significantly to the instability, and that reducing the liquid oxygen injector secondary volume would detune this cavity eliminating the instability.

(C) Under the Roller Bearing Durability Test subtask, 55 x 96.5 mm roller bearings were tested and evaluated for use in the 250K fuel turbopump. The proposed demonstrator fuel turbopump design has two 55 x 96.5 mm roller bearings, one located in front of the 1st-stage impeller and the other located between the 2nd-stage impeller and turbine. The fuel turbopump roller bearings operate at a maximum DN of about 2.65 million mm x rpm. These bearings operate in a liquid hydrogen environment that is provided by the propellant being pumped in the fuel turbopump. The roller bearing test rig that was used is essentially the same as the one used in Phase I, except for modifications to the load bearing mounting and to the drive turbine seal areas. This test rig has the capability of testing two bearings simultaneously at speeds up to 62,000 rpm with radial loads up to 2400 pounds. During the current program, which accumulated 85.1 hours of test time at 48,000 rpm, tests were conducted to evaluate the effects of roller length-to-diameter ratio, roller end-to-side rail clearance, internal clearance, and roller crowning on roller end wear and bearing durability. During all the tests, a 1700-lb radial load was applied to the load bearing resulting in an approximate 1445-lb radial load on the reaction bearing. Five bearing configurations surpassed the 10-hour goal test duration at the design operating conditions. Because of the limited scope of the bearing program and the many variables being evaluated, conclusions were necessarily made based on a single test of a particular bearing configuration unless abnormal test conditions indicated that a repeat test on a configuration was required. This technique was used to indicate the direction for subsequent tests in an effort to reduce the investigation to the more promising ar a. Based on the roller bearing tests to date, it appears that both roller end wear and skewing can be minimized or eliminated by increasing the negative diametral clearance required to maintain a load on the rollers on the unloaded side of the bearing, when the bearing is operating at design conditions. The most promising bearing configuration tested used stainless steel (AMS 5630) inner race and rollers; an outer race guided Armalon cage; a steel alloy (AMS 6265) outer race; single crown, L/D = 1.0 rollers with 0.020 inch roller end-to-inner race side rail clearance and 0.0043 inch negative diametral internal clearance. It is recommended that bearings of this configuration be used in the fuel turbopump.

(C) Under the Pump Inlet Evaluation subtask, nine basic inlet configurations were evaluated by electrical analog studies. Two configurations were selected as a result of these electrical analog studies for evaluation on the water test loop. These were a short radius elbow with turning vanes and a pancake inlet without guide vanes. An elbow inlet with guide vanes was the best design analyzed from a head loss and velocity distribution standpoint, and was most suitable for the liquid oxygen pump because of the severe space limitations at the fuel pump and inlet. The pancake inlet without guide vanes that was a more flattened design and would satisfy the envelope requirements of the fuel pump was selected as the second candidate for evaluation on the water test loop. Three inlet configurations were then tested on the water loop using an existing 350K oxidizer pump inducer fabricated under Contract NAS8-20540. These were: (1) a straight inlet to establish baseline inducer performance, (2) a 112-degree elbow inlet with turning vanes, and (3) a 112-degree flattened "pancake" inlet. Suction characteristics of the 350K inducer

with the straight inlet compared favorably with predicted levels. Peak suction specific speed was near 25,000. Suction performance with the elbow inlet compared favorably with that of the straight inlet and with predicted suction performance levels. Maximum demonstrated suction specific speed was 24,000. Suction performance with the pancake inlet also compared favorably with that of the straight inlet and with predicted levels of suction performance. Maximum demonstrated suction specific speed was 23,500. Indicated noncavitated performance with the straight inlet was about 15% lower than determined during oxidizer pump tests under Contract NAS8-20540 using liquid oxygen and liquid nitrogen as the pumped fluids. The noncavitated head coefficient versus flow coefficient slope was steeper with the elbow inlet and the head coefficients were higher at low flow coefficients than obtained with the straight inlet. The head coefficient flow coefficient characteristic with the pancake inlet was approximately the same level as with the straight inlet, but had a discontinuity between flow-to-speed ratios of 0.16 and 0.18. Higher noise levels emanate from the pancake inlet at low flow-to-speed ratios and also at high speeds indicating a possible structural problem. Large static pressure losses occur in the inlet section of both the elbow and pancake housings at low flow-to-speed ratios. These losses appear to be pump related and are accompanied by severe inlet pressure oscillations. The various inlet configurations were tested over the range of flow-to-speed ratios expected in the engine throttling range; however, maximum speed and flow rates were restricted by test stand limitations to about 40% of design. It is believed, however, that the test results can be extrapolated to design conditions.

(C) Under the Nozzle Fabrication Investigation subtask, the nozzle design and fabrication optimization studies were conducted and completed. To optimize the performance of an engine using a lightweight, two-position nozzle, it was necessary to design the nozzle to maintain the inner wall temperature as hot as possible. This level of temperature was controlled mainly by the material selection, material thickness, coolant flow rate, coolant velocity, and configuration geometry. A study of different heat exchangers was conducted. Several configurations were eliminated during this study, with only two candidates selected for further investigation. These were the corrugated inside and outside diameter configurations. Several configurations of the sheet metal support bands for the ring-stiffened translating nozzle under hoop compression were studied. Sample panels of the more promising configurations were fabricated and tested. Twenty-one thermal fatigue tests were conducted on segments of the sample panels. The proposed panel (0.005-inch thick corrugated inner sheet with 0.010-inch thick outer sheet) could not complete the required minimum of 300 thermal cycles at the predicted nozzle temperatures; in fact, the average was 33 cycles. The nozzle hot wall temperature had to be decreased to 1760°R, which is 400 degrees below that desired, before 300-cycle fatigue life could be achieved. Increasing the thickness of the corrugated sheet to 0.010 inch allowed the hot wall temperature to be increased to 2010°R for 300 cycles of fatigue life, while causing only a 10% increase in the total nozzle weight.

(U) Under the Controls Component Tests subtask, tests conducted on four different shutoff seal configurations for the main chamber oxidizer valve resulted in the selection of two seals for continued development and a

shaft lip seal package capable of meeting the demonstrator engine leakage goals. Translating seal rig tests verified the acceptability of formed Kapton and Teflon lip seals for translating shaft applications. Pressure balanced beryllium copper (AMS 4650) piston ring seals were designed for the preburner oxidizer valve, and tests indicated that the required actuator forces were reduced. A precision chrome plating was also found to be satisfactory as a bearing surface for the beryllium copper piston ring seals. A design analysis of high pressure separable flange coupling requirements was also conducted. The analysis was computerized and a hydrostatic test rig design was completed for substantiation testing. A finite element computer program was also adapted for coupling deflection and stress analysis because it would provide a versatile design tool. Hydrostatic stress and deflection testing was completed on two configurations of a 6-inch diameter aluminum pipe coupling rig, and the finite element program was modified to provide acceptable prediction capability.

(U) Under the Preburner Injector Development subtask, the design of the preburner injector for the demonstrator engine was completed, based on the test results obtained from the Supporting Data and Analysis task. Design studies were conducted on fabrication techniques that would simplify the fabrication and parts replacement for the demonstrator engine preburner injector. It was decided to incorporate the brazed one piece element design in the demonstrator engine preburner injector because of the reduced cost and simplicity of this design. Investment casting and diffusion bonding techniques were considered as possible methods of fabricating the preburner injector. However, certain problems, such as the use of caustic contaminants to remove the casting core eliminated these techniques from consideration. Analysis on the thermal low cycle fatigue (LCF) life problem in the preburner injector Rigimesh faceplate showed that no plastic strain existed for the worst case and, therefore, the Rigimesh is not limited in thermal low cycle fatigue life.

(U) Under the Main Burner Injector subtask, a design study was conducted to select the best design concept for the demonstrator engine. To ease fabrication difficulties and improve repairability, prime consideration was given to a multipiece injector design. It was proposed that the injector be built from pie-shaped segments or from individual spraybars brazed or welded into an oxidizer manifold. Design concepts using the single tapered tube spraybar with an increased flow area are superior in most respects to all other concepts, particularly in weight. It was also proposed that an investment cast injector, with the oxidizer injection elements simultaneously diffusion bonded in place, be considered. Casting the main burner injector in one single piece is presently beyond the state-of-the-art. Diffusion bonding the oxidizer injector elements into the cast spraybars is not impractical; however, considerable development would be required. Consideration was given to fuel faceplate support structure, structure-to-Rigimesh attachment, and faceplate assembly retention. A main burner igniter design study was conducted to analyze various concepts for integrating the main burner igniter into the engine transition case and main burner injector. This study included methods of adapting the igniter fabricated during Phase I (Contract AF04(611) - 11401) as well as new concepts that could reduce the size and complexity of the igniter system.

(C) Under the Nozzle subtask, designs of the primary nozzle and the two-position nozzle were initiated. The nozzle assembly for the XLR129-P-1 demonstrator engine will consist of two fixed sections that form the primary nozzle and a translating lightweight section as the two-position nozzle. The primary nozzle attaches to the main burner chamber at an area ratio of 5.3 and extends to an area ratio of 35. A design study indicates that the primary regeneratively cooled nozzle is mechanically feasible. The two-position nozzle coolant passages are designed to pass the coolant at a rate that keeps the inner skin of the nozzle at a temperature as high as possible in the axial direction to absorb maximum energy in the flow stream. The skin temperature is limited in the inlet region to avoid low cycle fatigue over the required life of the engine. The outer skin of the two-position nozzle will have a high circumferential thermal gradient because of the corrugated flow passages and the fin-cooled weld flats. The thermal stresses imposed on the outer skin by the gradient will be taken out in hoop tension. The outer skin of the two-position nozzle will be smooth; and this has three advantages. The stiffening bands can have an uninterrupted bonding surface, the outer skin thickness is based on strength requirements and not thermal requirements, and the corrugation cannot be constricted by thermal expansion.

(U) Under the Main Burner Chamber subtask, the design of this component was initiated. The main burner thrust chamber design is based on the copper wafer cooled thrust chamber demonstrated during Phase I (Contract AF04(611) - 11401). A study of the cooled wafer liner was conducted to provide a chamber liner that is not radially pressure loaded in the cylindrical portion and to reduce the bolt circle diameter of the main injector attachment flange for reduced weight. A number of main burner chamber liner configurations were studied for the most advantageous configuration. The selection of the best design was based on the following considerations; heat transfer and pressure drop, structural and mechanical integrity, and weight. Preliminary studies indicate that either a 32-tube or 96-tube design for providing coolant to the wafer liner coolant zones appears to be the most advantageous configuration. This is the configuration being analyzed in detail.

(U) Under the Transition Case subtask, a design analysis was initiated to determine the basic design approach for the transition case, gas flow ducts, and coolant liners. A design concept of intersecting segmented spheres is being proposed for the transition case configuration. Because a sphere is inherently a more efficient pressure vessel than a cylinder or cone, this concept will provide the following advantages:

1. Lighter construction because a thinner shell is required to resist pressure; material in tension not bending.

2. Easier construction because intersecting spheres provide circular intersections, where stiffening is required, instead of elliptical intersections for cylinders and cones, where even more stiffening would be required.

3. A decreased bending stress at the flanges and other boundaries because of the radial load component.

Five intersecting sphere configurations were studied initially; namely, three co-planar component designs and two canted component designs. Hand calculations and computer programs were conducted on each of these designs to determine if they could perform under the predicted pressures and stresses. Two of these designs; namely, one canted version and one co-planar version were selected for further study and model testing. In addition, a truncated spherical model was selected that simulated construction and load conditions anticipated for the inner duct centerbody. The truncated spherical model was tested under pressure until the proportional limit of the material was reached at local areas. A review of these data indicates good correlation between the test result and the predicted results. A model, which simulated the intersection of the basic sphere and a sphere segment for the co-planar component design, was tested. The results of these tests show that the loads required to reach the proportional limit of each model was generally higher than predicted because of the biaxial stress field. There were instances where applied loads were limited to lower values than predicted, because of bending concentrations around the ring and shell intersections resulting from weld mismatch. A thrust structure model, representing the canted component design was also tested. These tests indicated that the load in the shell is lower than the predicted value, and that the rings take a greater portion of the load than the shell because the load was distributed along the stiffest path, which was the intersection of the thrust pad and the three component rings. Studies were conducted on the internal ducts of the transition case that showed the canted concept was lighter weight than the co-planar concept, and that the ducts should be cooled.

(C) Under the Fuel Turbopump subtask, a preliminary design configuration has been initiated. The demonstrator engine requires that the fuel turbopump deliver liquid hydrogen at a flow rate of 99.3 lb/sec at a pressure of 5654 psia at its design point (mixture ratio of 5). The two-stage turbine must deliver approximately 49,872 horsepower to the pump and must operate at a minimum inlet temperature of 1986°R and at a maximum temperature of 2292°R at 100% thrust.

(C) Under the Oxidizer Turbopump subtask, a preliminary design configuration has been initiated. The demonstrator engine requires that the oxidizer turbopump deliver liquid oxygen at a maximum flow rate of 548 lb/sec with a pressure rise of 4603 psid at its design point (mixture ratio of 7) and a maximum pressure rise of 5737 psid at a mixture ratio of 5. The pump design incorporates a valve system that recirculates approximately 20% of the oxidizer flow back to the pump inlet to limit the discharge pressure to 6000 psia. The turbine must operate at a minimum inlet temperature of 1986°R and a maximum inlet temperature of 2292°R at 100% thrust. Preliminary analysis indicates that the turbopump must be capable of operating at a maximum speed of 25,925 rpm.

(C) Under the Fuel Low-Speed Inducer subtask, a preliminary design was completed. The demonstrator engine requires that the fuel low-speed inducer deliver hydrogen to the inlet of the fuel turbopump at a pressure level consistent with high speed operation of the fuel turbopump. The inducer must be capable of operating at a minimum NPSH of 60 ft over a

hydrogen inlet temperature range from 1 atmosphere boiling temperature to 45°R. The inducer will be designed with a suction specific speed of 46,800 and a maximum pressure rise of 109 psid. The low-speed inducer will be lightweight, compact and capable of stable operation over the engine operating range.

(C) Under the Oxidizer Low-Speed Inducer subtask, a preliminary design was completed. The demonstrator engine requires that the oxidizer low-speed inducer deliver oxygen to the inlet of the oxidizer turbopump at a pressure level consistent with high speed operation of the oxidizer turbopump. The inducer must be capable of operating at a minimum NPSH of 16 ft over an oxygen inlet temperature range from 1 atmosphere boiling temperature to 180°R. The inducer will be designed with a suction specific speed of 40,000 and a maximum pressure rise of 253 psid. The low-speed inducer will be lightweight, compact, and capable of stable operation over the engine operating range.

(U) Under the Control Systems subtask, a control system analysis was conducted of the XLR129-P-1 rocket engine cycle to determine the required control points for satisfactory steady-state operation. The preburner oxidizer and fuel valves, the main chamber oxidizer valve, oxidizer pressure limit valve and oxidizer low speed inducer turbine area actuator were selected to provide the necessary regulation. Additional endurance tests were conducted on the cam-actuated and hoop-type main chamber oxidizer valve shutoff seals. The hoop-type seal was selected for incorporation into the demonstrator engine valve design. An improved pressure balanced piston ring seal design for the preburner oxidizer valve was completed. Test rig actuator force tests with the new design rings in the existing valve confirmed the reduced load characteristics planned for the demonstrator engine valve design, which is in process. Design selection studies were conducted for the preburner fuel valve and propellant vent valves. An offset shaft, shaped disk with spherical sealing surface, butterfly type design was selected for the preburner fuel valve. A single-acting, normally closed, two-position, ball-type design with pneumatic actuator was selected for the propellant vent valves. The design layouts for these valves are in process. The finite element computer program was used to design an Inconel 718 (AMS 5663) nickel alloy, 0.002 inch deflection (at the seal), cantilevered flange, static seal test rig. The parts detail drawings are in process for the basic test rig and modifications to allow testing six face type static seals. Analog and digital program models of the engine steady-state design and off-design performance characteristics are in process. These models will be forwarded to prospective control system vendors along with the engine command unit, transducers, and valve actuaters purchase specification. The purchase specification is being drafted and will be issued early in the next period.

(U) Under the Engine Integration and Demonstration subtask, a series of analytical studies were conducted to provide a balanced engine cycle that would fulfill the demonstrator engine requirements and characteristics. An engine arrangement study was conducted to determine the configuration of the transition case. An arrangement with the turbopumps and preburner in a common axial plane (co-planar) and spaced 120 degrees apart was

selected. An engine plumbing study was also conducted to determine the plumbing configuration requirements, and to derive ground rules to govern material selection and fabrication. A fabrication feasibility study was conducted to define the configuration problem areas prior to initiating the major engine component design.

SECTION III
CONCLUSIONS AND RECOMMENDATIONS

(U) Studies conducted during this report period resulted in the following conclusions and recommendations, which are listed for each of the major subtasks.

A. FIXED FUEL AREA PREBURNER INJECTOR EVALUATION

(C) 1. The 0.124-inch inside diameter element was selected for the fixed area preburner injector with slot areas to provide the required engine cycle injection pressure drops.

B. ROLLER BEARING DURABILITY TESTS

(U) 1. Roller skewing, which accounted for most of the bearing failures during the current program, was not found to be related to roller end wear or roller end-to-side rail clearance if sufficient negative internal clearance was incorporated in the bearing.

(U) 2. The increased length-to-diameter ratio, triple crown rollers did not demonstrate the anticipated improvement in resistance to roller skewing over L/D = 1.000 single crown rollers. The longer L/D rollers demonstrated more skewing tendency than the L/D = 1.0 rollers with the same internal clearance and side rail clearance.

(U) 3. The most promising bearing configuration tested used stainless steel (AMS 5630) inner race and rollers; an outer race guide Armalon cage; a steel alloy (AMS 6265) outer race; single crown, L/D = 1.0 rollers with 0.020 inch roller end-to-inner race side rail clearance and 0.0043 inch negative diametral internal clearance. It is recommended that bearings of this configuration be used in the fuel turbopump.

C. PUMP INLET EVALUATION

(U) 1. The elbow inlet appears to be superior to the pancake inlet and is recommended for both the fuel and liquid oxygen pumps although some slight modification to the inlet may be required to fit this configuration into the engine envelope on the fuel pump inlet.

D. NOZZLE FABRICATION INVESTIGATION

(U) 1. It was concluded that the material most suitable for constructing the two-position nozzle was Inconel 625 (AMS 5599), and that the internal corrugated design was the most feasible to fabricate. An important factor in this selection was that the design allowed the use of standard stiffener bands on the [illegible] surface.

(U) 2. It was also concluded that stiffener bands of the "dunce hat" design would be used for the optimum lightweight configuration.

(U) 3. The progressive die forming process produced good corrugation detail with minimum elongation and was selected for final fabrication. Resistance seam welding the assembly provided the easiest and most reliable construction method and produced high quality stiffener bands, as substantiated by the samples fabricated and the hydrostatic tests performed.

(U) 4. The 0.010- to 0.010-inch thick nozzle configuration using the internal corrugation design is recommended for the two-position nozzle design.

E. CONTROLS COMPONENT TESTS

1. Main Chamber Oxidizer Valve

(U) 1. The silver-plated hoop seal and the cam-actuated seal designs were considered to be acceptable shutoff seals for continued development for the canted shaft butterfly valve.

(U) 2. The strap-actuated and looseleaf shutoff seals did not appear to warrant further effort.

(U) 3. Laminated Kapton F lip seals met the leakage and durability goals and were recommended for this application.

(U) 4. It was recommended that development of the hoop seal be continued to improve manufacturing methods and cleaning capability.

(U) 5. It was recommended that development of the cam-actuated seal be continued to improve durability.

2. Preburner Oxidizer Valve

(U) 1. Precision chrome coating was selected for the preburner oxidizer valve application because the plating techniques are sufficiently developed. The application of molybdenum-chromium will require further coordination with an outside vendor or in-house plating shop to produce consistent results. Further development of molybdenum-chromium was recommended for extremely high load applications where the wear characteristics of precision chrome is not acceptable.

(U) 2. The pressure balanced piston rings provided acceptable wear and leakage characteristics and a reduction in actuation force as compared to the unbalanced rings; however, further force reduction is desirable to minimize the actuator power requirements.

(U) 3. A lip seal was not recommended for the balance piston because of the high leakage encountered.

(U) 4. Reduction of the seal package size of the preburner oxidizer valve is possible by eliminating one shaft seal and changing the seal configuration to a Kapton-Teflon lip seal. A laminate configuration of KKTTK was recommended for application at the primary and vent shaft seal locations.

3. Static Seals

(U) 1. Supporting data for a satisfactory seal rig design was accomplished during this report period. The finite element computer program, as adapted to coupling analysis, will be satisfactory for optimization of coupling flanges.

(U) 2. It was recommended that static seal test rigs be designed for the minimum deflection consistent with the demonstrator engine weight goals. The finite element computer program should be used to analyze all demonstrator engine flanges to limit deflection to the values selected for the static seal test rigs. Both axial and radial type static seals should be procured and tested in the rigs designed under the component development phase of this program.

F. PREBURNER INJECTOR

(U) 1. The design of the preburner injector for the XLR129-P-1 demonstrator engine was completed. A dual-orifice tangential-entry oxidizer, fixed area fuel injector was selected. Selection of this injector concept was based on test results obtained under the Supporting Data and Analysis task.

G. MAIN BURNER INJECTOR

(U) 1. The single tapered tube spraybar is the concept recommended for the demonstrator engine main burner injector.

(U) 2. It was concluded that a straight single tube spraybar, which could either be cast or machined from a forging, is desirable. This type of spraybar is slightly heavier than an angled type of single tube spraybar design

(U) 3. The existing Phase I (Contract AF04(611)-11401) igniter hardware cannot be used in the demonstrator engine transition case and injector without modification.

H. NOZZLES

(U) 1. The recommended primary nozzle design has a single pass heat exchanger at the inlet end and a double pass heat exchanger at the exit end.

(U) 2. It is recommended that the two-position nozzle be constructed using the internal corrugated, smooth outer skin type of structure.

I. MAIN BURNER CHAMBER

(U) 1. Structures and heat transfer studies of conceptual design configurations are in process. The final design selection will be made after completion of these studies.

J. TRANSITION CASE

(U) 1. It was concluded that for the overall transition case design, the co-planar transition case offers the best solutions regarding the inner duct design, cooling, thrust load handling, assembly, and manufacturing.

K. FUEL TURBOPUMP

(U) It was concluded that the preliminary design configuration of the fuel turbopump should incorporate the following features:

1. Integral high-speed axial-flow inducer

2. Two-stage pump with centrifugal impellers, axial entry and double discharge

3. Double acting hydrostatic thrust balance piston

4. Full-admission, axial-flow, two-stage, pressure-compounded turbine with cooled disks and uncooled airfoils

5. Two antifriction roller bearings.

L. OXIDIZER TURBOPUMP

(U) It was concluded that the preliminary design configurations of the oxidizer turbopump should incorporate the following features:

1. Integral high-speed, axial-flow inducer

2. Single-stage shrouded impeller with axial entry and double discharge

3. Single-acting hydrostatic thrust balance piston

4. Full-admission, axial-flow, two-stage pressure turbine with cooled disks and uncooled airfoils

5. Two antifriction ball bearings.

M. FUEL LOW-SPEED INDUCER

(U) It was concluded that the preliminary design configuration of the fuel low-speed inducer should incorporate the following features:

1. Helical axial flow inducer
2. Single acting hydrostatic thrust balance piston
3. Two-stage, axial-flow, partial-admission impulse turbine
4. Two antifriction ball bearings.

N. OXIDIZER LOW-SPEED INDUCER

(U) The preliminary design configuration for the oxidizer low-speed inducer was initiated. However, a complete hydraulic analysis of the inducer has not yet been performed, but it is anticipated that a helical axial flow inducer will be incorporated. It was concluded that a thrust balance piston is required. The drive turbine will be a single-stage, radial inflow design. A variable-area turbine is an ideal approach to provide variable pressure drop to meet the power requirements of the inducer over the entire operating range of the engine.

O. CONTROL SYSTEM

(U) Engine cycle studies indicate that control components will be required at five points in the demonstrator engine: preburner fuel and oxidizer supply lines, main burner oxidizer supply line, oxidizer low-speed inducer turbine inlet area, and oxidizer pump recirculation line. It is recommended that valve designs for these locations be completed for incorporation into the demonstrator engine.

1. Main Chamber Oxidizer Valve

(U) 1. The silver plated hoop-type shutoff seal provided the most consistent extended endurance test results, met all of the test goals, and was still serviceable at the end of the test.

(U) 2. The cam-actuated shutoff seal ambient temperature leakage was less than that of the hoop seal, but the cryogenic temperature leakage was greater and the seal element was not as durable as that of the hoop seal.

(U) 3. Laminated Kapton/FEP Teflon lip seals continue to be recommended for the valve shaft seals.

(U) 4. It is recommended that the silver plated hoop seal be incorporated in the main chamber oxidizer valve design for the demonstrator engine.

(U) 5. It is recommended that development of the cam-actuated seal (as a back-up to the hoop seal) be discontinued.

2. Preburner Oxidizer Valve

(U) 1. Precision chrome coating has acceptable wear characteristics and has been selected for the preburner oxidizer valve housing and sleeve. Further development of molybdenum-chromium plating is recommended for extremely high load applications where the wear characteristics of precision chrome is not acceptable.

(U) 2. Balanced piston rings will provide acceptable wear characteristics and satisfactory actuation force levels, and are recommended for the demonstrator engine valve.

(U) 3. A shaft lip seal laminate configuration of KKTTK is recommended for application at the primary and vent shaft seal locations.

3. Preburner Fuel Valve

(U) 1. The valve selection study completed for this control point requirement resulted in selection of a modified butterfly type valve for this application. Completion of the selected valve design, parts procurement and testing are recommended for the next period.

4. Oxidizer Pressure Limit Valve

(U) 1. A recirculation valve for the oxidizer turbopump will be required to limit the oxidizer turbopump discharge pressure. The valve will only be required to operate near maximum thrust and minimum mixture ratio. A scheduled valve position as a function of thrust and mixture ratio is the recommended control mode.

(U) 2. Completion of a selection study and valve design for the demonstrator engine is recommended.

5. Oxidizer Low-Speed Inducer Actuator

(U) 1. Analysis of the specific requirements for this control system component will not be possible until the low-speed inducer turbine design concept is firm. The actuator requirements and design type selection for the demonstrator engine will be accomplished at that time.

6. Static Seals

(U) 1. Supporting data for satisfactory seal rig design was completed during this period. The finite element computer program, as adapted to coupling analysis, will be satisfactory for optimizing coupling flange designs.

(U) 2. The finite element analysis showed that the cantilevered flange type coupling with 0.002-inch deflection is the most desirable configuration for a static seal rig from the standpoints of envelope and weight. Six face-type static seals were found to have deflection and sealing capability to meet the engine design goals according to the manufacturers.

(U) 3. A finite element analysis of the Battelle Memorial Institute coupling design for the use of AFRPL Bobbin seal indicated that it had moderate deflection at the seal, and was excessively bulky and heavy.

(U) 4. It is recommended that six face-type seals be tested in the 0.002-inch deflection cantilevered flange seal rig. A seal rig capable of meeting the engine weight and envelope requirements should be designed for the AFRPL Bobbin seal.

P. ENGINE INTEGRATION AND DEMONSTRATION

(U) 1. An engine cycle balance, designated cycle No. 6, has been developed that meets the demonstrator engine requirements and characteristics. This cycle will be the basis for the design of the XLR129-P-1 engine.

(U) 2. Either the canted or co-planar transition case designs can be reasonably packaged and no significant advantage is obtained from one design over the other. Selection of the transition case, therefore, should be based on component structural requirements.

(U) 3. The calculated head loss values used in the engine cycle balance are representative of the engine plumbing system.

(U) 4. The material that appears most desirable for use in the plumbing lines is Inconel 718 (AMS 5589) because of its high strength and elongation. The use of castings for the plumbing lines is a possibility, however, castings generally have a lower fatigue and yield strength than wrought alloys along with lower elongations. The use of bent tubes for the plumbing lines is another possibility. All of the vendors contacted have had extensive experience in similar lower pressure aerospace plumbing.

SUPPLEMENTARY

INFORMATION

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

March 27, 1969

In reply please refer to:
MFS:RPSmh:Cont. Adm.

Major Ernie D. Braunschweig, RPREB
Air Force Rocket Propulsion Laboratory
Edwards, California 93523

Dear Major Braunschweig:

Per our letter, MFS:RPSmh:Cont. Adm., dated February 17, 1969, we transmitted PWA FR-2972, Air Force Reusable Rocket Engine Program XLR129-P-1, First Annual Report, AFRPL-TR-69-3, dated January 1969.

Errata

Subsequent to the transmittal of the subject report, the security classification of two paragraphs was found to be inaccurately designated. Please make the following ink corrections to all copies of the report, so that readers will be properly advised.

(a) Change the classification of Paragraph No. 3 of Part B on Page 15 in Volume 1 from Unclassified (U) to Confidential (C).

(b) Change the classification of the 3rd Paragraph on Page 494 in Volume III from Confidential (C) to Unclassified (U).

AD-395-106

Very truly yours,

UNITED AIRCRAFT CORPORATION
Pratt & Whitney Aircraft Division

M. F. Samples

M. F. Samples
Senior Contract Administrator
Florida Research and Development Center

cc: All recipients of PWA FR-2972

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